Lasernet Machinery Monitoring Technology

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Abstract: The analysis of debris present in machinery lubricating systems has the ability to provide fault-specific information in a timely manner to support diagnostics and prognosis of machinery maintenance. This capability allows the avoidance of catastrophic failures and enables improved cost-effective asset-management philosophies, especially in the area of timely maintenance and reduction of maintenance induced failures. Essential to achieving these asset management and condition based maintenance goals, are technologies that can provide reliable early identification of fault or failure mechanisms and the degree of degradation of the machine's performance capability. These technologies must also assess the effect of the performance degradation with its impact on the machine's mission requirements, the system that it supports in a shipboard environment or the affected factory environment. The LaserNet Fines instrument delivers a technology which has significant potential in these areas. Using laser imaging techniques and advanced image processing software LaserNet Fines determines the type, severity and rate of progression of mechanical faults by measuring the size distributions, rate of production and the morphological analysis of debris particles in fluids. This instrument also has the capabilities of identifying contaminants, free water and fibers in a wide range of fluids such as mineral and synthetic lubricants and hydraulic fluids. This paper discusses these capabilities and features of the LaserNet Fines instrument along and with examples from both field and laboratory evaluations.

Key Words: image analysis; LaserNet Fines; particle counter; wear debris analysis.

Introduction: Advanced oil debris monitors are an important part of comprehensive condition based monitoring systems. An important aspect of these monitors is the ability to identify the type and severity of faults as well as their presence. LaserNet Fines (LNF) is a fault-specific, optically-based oil debris monitor developed as part of the Condition Based Maintenance (CBM) program sponsored by the Office of Naval Research (ONR).

Ferrography has long been the workhorse for inferring wear mode. The weak points of ferrography have always been the time to prepare the sample, the requirement for a skilled analyst, and that the assessments are relatively qualitative in view of the limited numbers of particles that an analyst can examine in a reasonable time. The morphological analysis of wear debris is a well-known laboratory analytic technique for the assessment of machinery health [1-4]. Work has been done to develop computer-assisted image analysis packages such as CASPA [5], CAVE [6] and SYCLOPS [7] to make the identification of wear debris less dependent upon a human expert. These also rely heavily on correct sample preparation to separate individual debris particles for analysis. LNF automatically uses particle morphology to determine the type, severity, and rate of progression of mechanical faults by retaining the size distributions, rate of production, and shape features of debris particles [8-10]. It also determines water, fiber, and particulate contamination of hydraulic and fuel systems.

LaserNet Fines Technology: The basic operating principle of LNF is illustrated in Figure 1. A representative oil sample is drawn from the lubricating system and brought to the unit. The oil is drawn through a patented viewing cell that is back-illuminated with a pulsed laser diode to freeze the particle motion. The coherent light is transmitted through the fluid and imaged onto an electronic camera. Each resulting image is analyzed for particles, with several thousand images ultimately used to determine the characteristics of the suspended particles and to obtain good counting statistics. Concentrations are measured for particle sizes between 5µm to over 100µm. For wear particles in lubricating oil, the instrument displays particle size in terms of maximum chord. For particles in hydraulics, it displays the size in equivalent circular diameter for compatibility with ISO cleanliness codes. In either fluid, shape characteristics are calculated for particles greater than 20µm, and the particle is classified into either a wear category or contaminant category. Classification is done with an artificial neural network that was developed specifically for the LNF system. Shape features were chosen to give optimal distinction between the assigned classes of fatigue, cutting, severe sliding, oxides, fibers, water bubbles, and air bubbles (Figure 2). An extensive library of particles, which were identified by human experts, was used to train the artificial neural network.

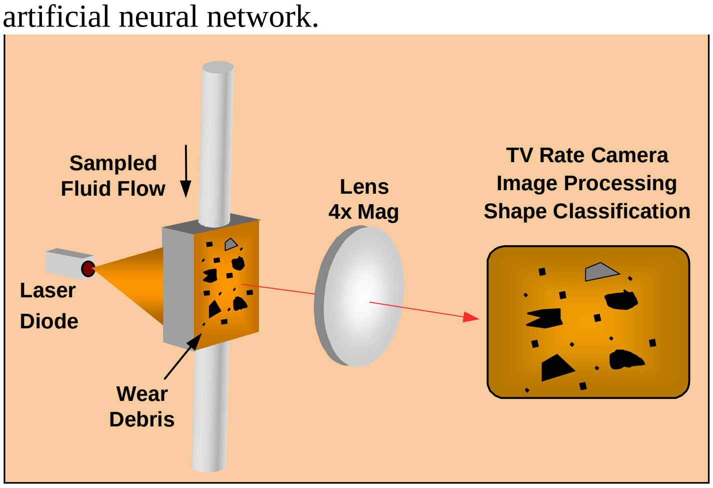

Figure 1. LaserNet Fines Operating Principle.

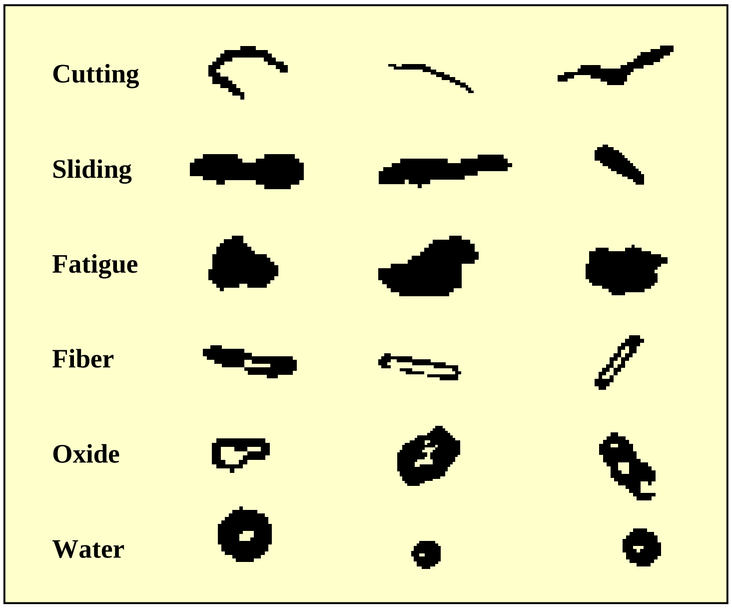

Figure 2. Examples of Particle Class Morphology.

<u>LaserNet Fines Benchtop Instrument:</u> The LNF instrument, shown in Figure 3, is capable of operating with fluids having viscosities up to 350 cst at room temperature and particle concentrations greater than 1,000,000 particles/mL. It is compatible with synthetic and mineral-based lubricants, hydraulic, and gearbox oils. The unit automatically compensates for each fluid's opacity and soot levels. Total test time, from sample preparation to flushing the system for the next use, is less than 7 minutes.

LNF has a touch panel graphical user interface on its top face for quick viewing by operators. Mouse and keyboard inputs are also available if preferred by the operator. All required operator actions are directed by the menu system – from agitating the sample and placing it in the on-board ultrasound unit through flushing the system for the next use.

Analytical results are presented on the instrument display in tabular and graphical forms (Figures 4-6), and are saved internally for trending with prior results from the same oil system. Trending graphs, which serve as the basis for machine condition assessment, are provided for each of the debris categories as well as total particle count and large particle fraction. Sample particle distribution statistical calculations, such as mean particle size, standard deviation and largest particle size, are determined for each debris category. An Ethernet interface may connect to an external computer system to transmit captured data. The results of the sample analysis are transmitted as text files that can be read by external condition assessment systems for incorporation into larger CBM systems.

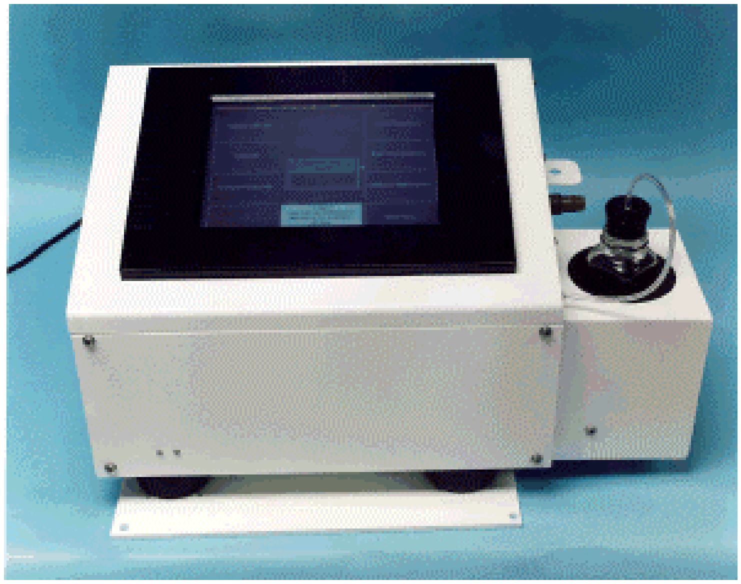

Figure 3. LASERNET FINES Instrument.

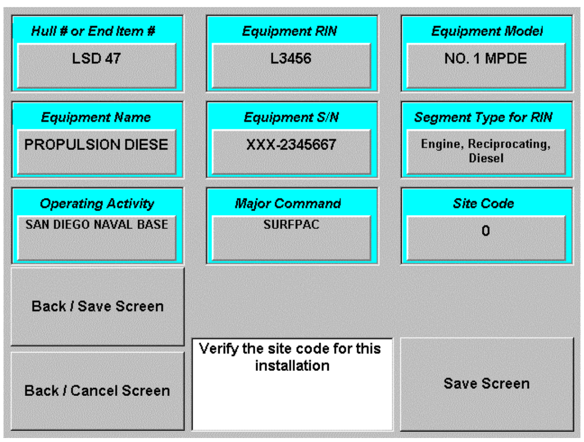

Figure 4. Equipment Information Screen.

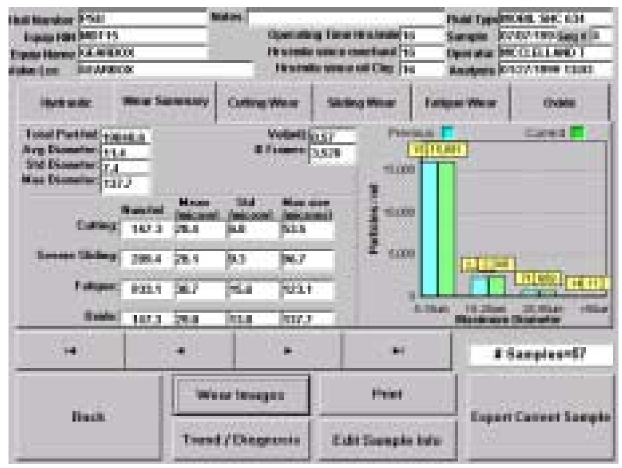

Figure 5. Sample Lube Oil Results Screen.

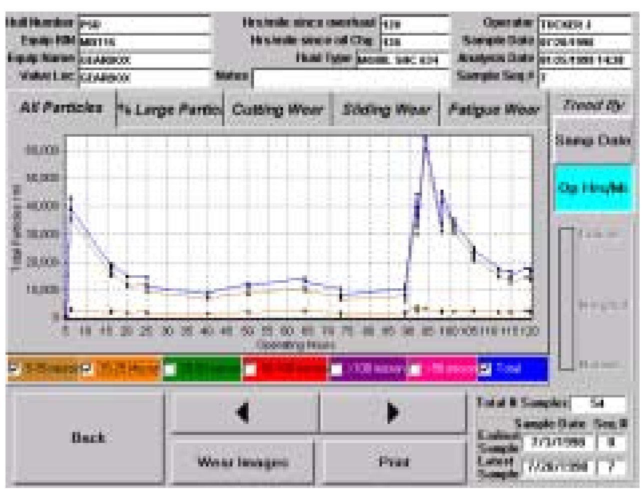

Figure 6. Sample Trend Graph by Wear Type.

Comparison to Particle Counters: LNF performs the same function of traditional laser particle counters – with distinctive enhancements that take the instrument's capabilities into the domain of analytical ferrography. LNF uses a two-dimensional sensing array versus the particle counter's one-dimensional array. This added spatial diversity allows LNF to examine higher particle concentrations and to extract particle morphology. With the ability to recognize shape, the particle counts of LNF are not contaminated by the presence of air bubbles or free water. Instead, those items are both subtracted from the debris counts, with the free water fraction identified separately. The remaining wear debris and filter fibers are included in the total counts and are also displayed in their own distributions.

LNF also works well in diesel lubricants with high soot levels. Soot particles are typically less than 0.1µm[11] and tend to obscure particle detector light sources. This condition renders traditional laser particle counters unusable unless the sample is first diluted, a procedure that is both cumbersome and error-prone. LNF performs a baseline measurement of fluid opacity prior to each analysis and makes use of the information to adjust the laser power and normalize the acquired image.

Calibration of laser-based particle counters has always been an issue, particularly with the recent changes in the calibration standard from ACFTD to MTD. Today, many particle counter vendors request that you order an instrument calibrated to your preferred standard. There are three primary problems with the way existing particle counters determine the size of particles:

- First, they use a point source detector instead of LNF's two dimensional detector. This is analogous to trying to determine the size of an automobile by knowing ahead of time how fast it is going and then listening to the sound it makes as it passes by. LNF operation is more analogous to standing a known distance from the path of the vehicle and taking a photograph as it passes.
- Second, they must be calibrated and used at a specified flow rate. The accuracy of the detection channels rely on a known flow rate for proper counting and for determining the total sample volume. The LNF detector is highly immune to flow rate variation because it freezes particle motion with a short laser pulse. Sample volume is known from the fixed dimensions of the viewed volume and the number of frames processed.
- Last, traditional obscuring laser particle counters misrepresent the size of oxides (e.g. silica, test dust) because these particles can appear to have translucent centers (Figure 2) at the wavelengths used by the laser. Thus after being calibrated with MTD, an obscuring laser particle counter will count a 20µm metal fatigue particle as being larger than 20µm because it blocks more light than a 20µm MTD particle. LNF uses image processing to "fill-in" the translucent centers before calculating the particle's equivalent circular diameter, thus properly reporting the size of oxides and other debris without special calibration.

LNF does not require calibration with a Standard Reference Material because the measurement accuracy is intrinsic to its configuration. Its particle size measurements rely on the camera's pixel size and the magnification power of the optics – both are fixed elements which remain virtually unchanged over time. The measurement volume relies on those fixed elements and also on the thickness of the viewing cell, which is fixed and does not significantly change with time or operating temperature.

	Analysis Time (Volume)	Flush Time	Coincidence Limit	Soot / Opacity	Free Water	Filter Fibers	Calibration
Particle Counter	1.5 min (~20mL)	0.5 min	<$90x10^3$ p/mL	Skews Count	Skews Count	Skews Count	To Selected Standard (6 months)
LaserNet Fines	2.3 min (.65mL)	1.5 min	>$1x10^6$ p/mL	Auto Baselines	IDs Separate	IDs Separate	Intrinsic (Not Required)

Table 1. LNF Compared to Laser Style Particle Counters.

LNF sizing and counting accuracy have been validated against Particle Counter Calibration Fluid 2.8 mg/L ISO Medium Test Dust in MIL-H-5606 hydraulic fluid from Fluid Technologies and the results are shown in Figure 7. In this plot, the particle size distribution is in terms of equivalent circular diameter. These results are compared with the particle size distribution determined by NIST for their Standard Reference Material SRM-2806. The FTI fluid is similar to the SRM-2806 they supplied to NIST, but has an uncertified particle size distribution. Above 7µm the LNF results lie well within the measurement uncertainty of the NIST standard, with the LNF measurements being low in the 5-7µm range due to detector quantization rolloff. NIST does not certify the distribution above 30µm because of the uncertainties associated with the low counting statistics.

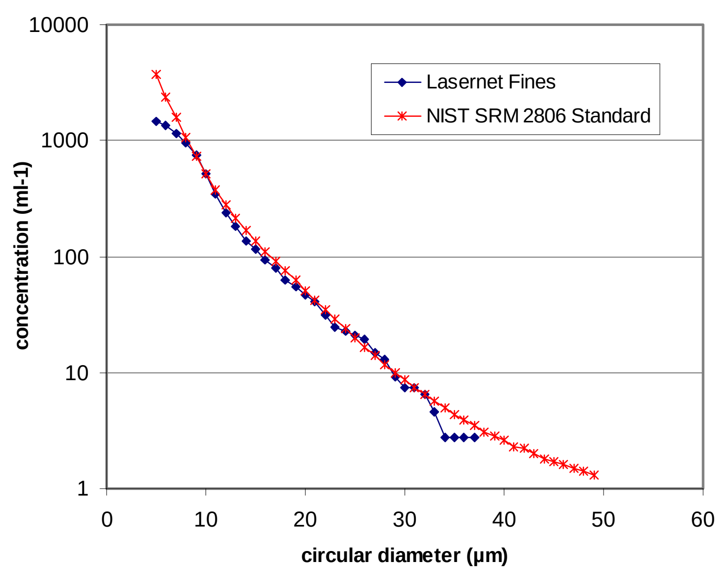

Figure 7. Comparison of LNF Equivalent Circular Diameter Particle Distribution for FTI-ISOMTD Fluid and NIST Particle Distribution for SRM 2806.

<u>Comparison to Ferrography:</u> Ferrography has long been a standard method for determining the type of wear mechanisms and severity of faults in lubricated machinery. The drawbacks of ferrography have been threefold: first, the test is time consuming; second, for meaningful results a trained analyst is required; and third, the ultimate result is strictly qualitative. Each analyst has his own methodology and preferences for analyzing a prepared slide. Even though most oil analysis labs diligently train their analysts to think the same, the inconsistencies are still present and even more obvious from lab to lab. Analysts do not have time to characterize and count all the large wear and debris particles that are on a typical slide. This is where LNF bridges the gap, providing insight into wear mechanisms and fault severity in a fraction of the time and without the need for a highly trained analyst. LNF counts and classifies all particles in its viewing cell to provide quantitative, repeatable measurements useful for trending and the early assessment of machine condition.

	Prep Time	**Analysis Time**	**Debris ID**	**Ferrous / Nonferrous ID**	**Free Water**	**Operator Skill Level**	**Results**
Analytical Ferrography	20 min	5-15 min	Morphology & Surface Features	Color / Hotplate Changes	Not Detectable	High (Analyst)	Subjective Qualitative
LaserNet Fines	2.5 min	2.3 min	Morphology	None	IDs Separate	Same as Particle Counter	Quantitative (Wear Particle Counts)

Table 2. LNF Compared to Ferrography.

<u>Wear Particle Case Study – Gearbox Accelerated Failure Test:</u> Accelerated gearbox failure tests were conducted at Pennsylvania State University on their Mechanical Diagnostic Test Bed (MDTB) Facility under the ONR CBM program. These tests were conducted on single-reduction 10 hp gearboxes. The gearboxes were run-in for approximately four days at maximum normal load provided by an electric generator on the output shaft. After that, a 3X overtorque was applied and the system then ran to failure. The system was stopped approximately every two hours for bore site inspection and oil sampling. LNF results from one run are shown in Figure 8. In Fig. 8a, histograms of the total particle concentrations are shown for different particle size ranges. Corresponding bars in the four size ranges are from the same sample. Oil samples were drawn at successive times during the test as indicated in the figures. A similar set of data for the particles classed as fatigue, severe sliding and cutting wear are shown in Figures 8b, 8c, and 8d, respectively. All particle concentrations are corrected for fluid dilution as the gearbox lubrication level was topped off with clean oil to replace each extracted sample.

The first sample in Figure 8 was taken at the end of the run-in period, with successive samples taken during overtorque operation. The sample location was changed between the 2 p.m. and 4 p.m. samples, accounting for the change in total particles counted at those two sample times. Near the end of the test, several teeth on the output gear broke before the 5 a.m. sample. In Figure 8a, the total particle concentration in the 5-15μm size range shows a general decrease during the run, which was due to gradual removal of debris generated during the run-in period as samples were drawn and replaced with clean fluid. In Figure 8b, however, an increasing concentration of fatigue particles are seen in several of the size ranges after the 3X overtorque was applied. This behavior is apparent well in advance of the ultimate failure and is probably related to the excess wear conditions that lead to failure. Similar increases in the concentration of severe sliding and cutting wear particles were not seen in any of the size ranges (Figures 8c and

8d). An increase of fatigue particles would be expected in such an overtorque situation where excessive force is concentrated along the gear pitch line where rolling action occurs.

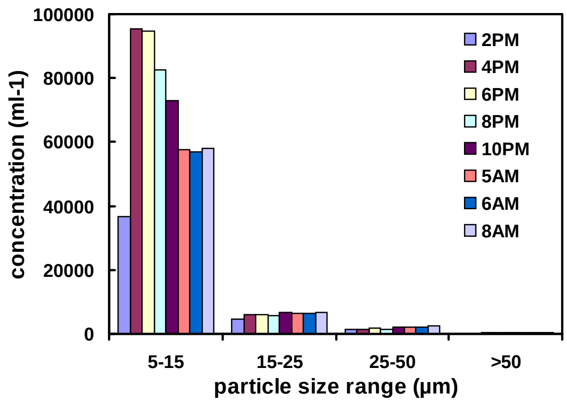

Figure 8a. Gearbox Total Particle Concentration Distributions.

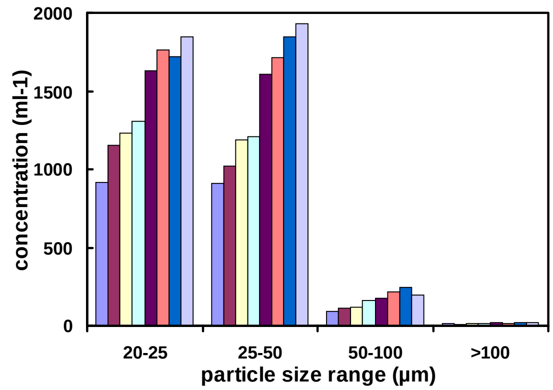

Figure 8b. Gearbox Fatigue Particle Concentration Distributions.

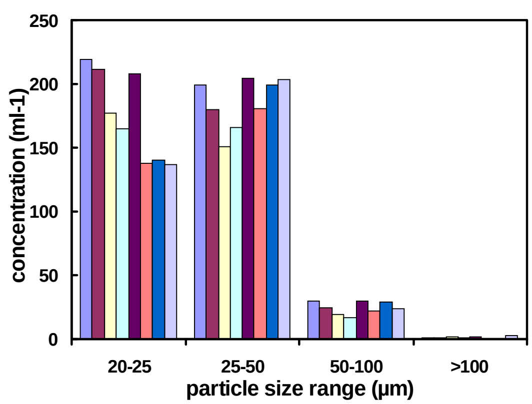

Figure 8c. Gearbox Severe Sliding Wear Particle Concentration Distributions.

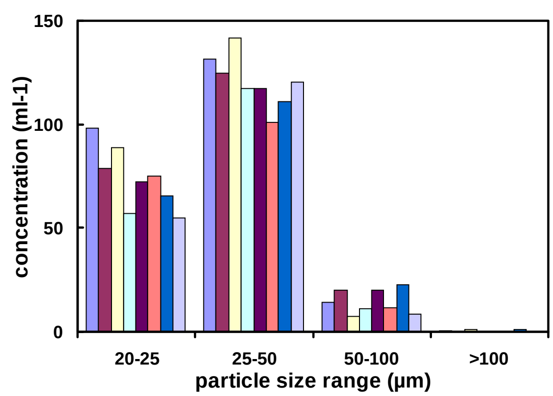

Figure 8d. Gearbox Cutting Wear Particle Concentration Distributions.

<u>Trial Sites:</u> LNF instruments have been deployed at shipboard and land-based facilities around the world. These sites include:

- ONR Research Vessel, *Thomas G. Thompson*, based out of Seattle, Washington
- Defense Evaluation and Research Agency (DERA), Pyestock, England
- *USS Rushmore* in the Pacific Fleet
- Newport News Shipbuilding, Newport News, Virginia
- Advanced Directorate of Materials and Monitoring (ADM&M), Gosport, England
- Defense Science and Technology Organization (DSTO), Rockingham, Western Australia
- Joint Oil Analysis Program (JOAP) Mid-Atlantic Testing Lab, Norfolk, Virginia
- Army Oil Analysis Program (AOAP), Fort Campbell, Kentucky
- National Tribology Service, Peabody, Massachusetts

These sites were selected to perform LNF analysis of shipboard and aircraft equipment for baselining, to look for mechanical fault signatures, to develop features of the wear debris analysis that can be related to machinery condition, get users input on functionality changes, and to identify any additional analysis capabilities which would benefit LNF.

R/V Thomas G. Thompson: A LNF unit is installed on the ONR ship *R/V Thomas G. Thompson* to monitor shipboard equipment which included external steerable drive pods, propulsion diesels, cranes, hoists and winches. Initially measurements for the steerable drive were made at a shared sump location which collected fluid from the upper and lower steerable drive gearboxes. Measurements at this location proved unsatisfactory due to large amounts of condensed water and accumulated debris which were not representative of current gearbox operation. This measurement location also did not allow differentiating debris from port and starboard pods. The gearbox fluid return lines were modified to allow sample measurements on the fluid as it exited the gearboxes. Figure 9 shows the effect of the change of sampling location on measurements of the total particle concentration.

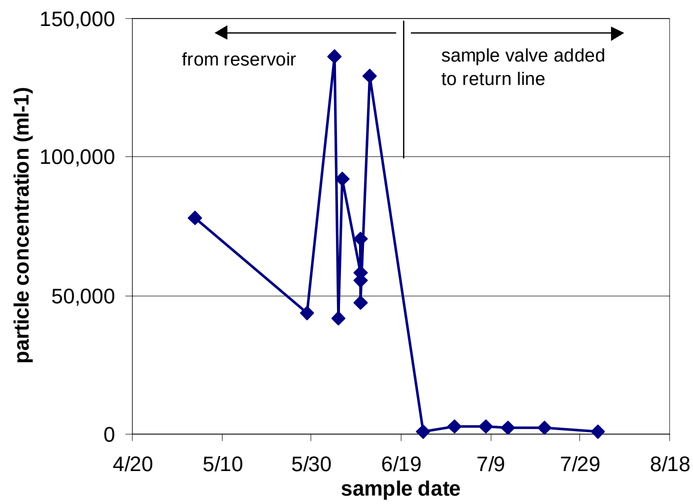

Figure 9. Effect of Changing Oil Sample Location on *R/V Thompson* Gearbox Total Particle Concentration Measurements.

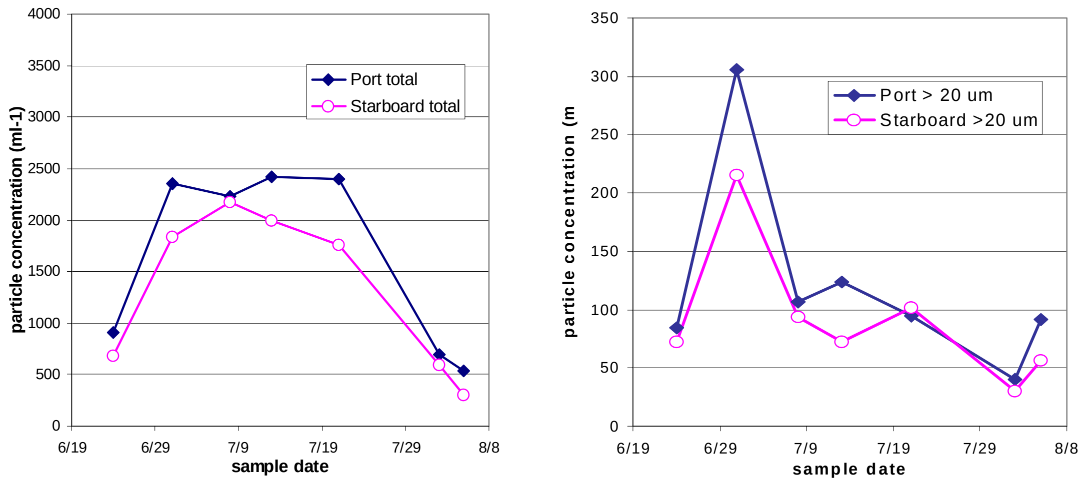

Figure 10. Total and Large Particle Concentration Measurements for Port and Starboard Gearboxes on Board *R/V Thompson*.

Oil samples taken from the return lines from the port and starboard side gearboxes are shown in Figure 10. Both gearboxes show similar time histories in terms of total particle and large particle (> 20μm) concentrations. This reflects that both gearboxes underwent similar usage profiles.

DERA : This site analyzes oil samples from operational aircraft by using a scanning electron microscope (SEM) and AC magnetometer device to examine magnetic plug debris samples. Some historical magnetic plug samples were reconstituted by removing them from the tape adhesive using mineral spirits and were suspended in filtered lubrication oil. Figure 11 shows a comparison of the LNF total particle concentration measurements divided by the hours the magnetic plug was inline and the scaled hourly wear rate magnetometer measurements for an aircraft gearbox. In this gearbox, increasing wear debris was measured up until the accumulation of 250 operating hours, at which time maintenance repairs were taken. Good agreement is seen between the LNF instrument measurements and the magnetometer readings.

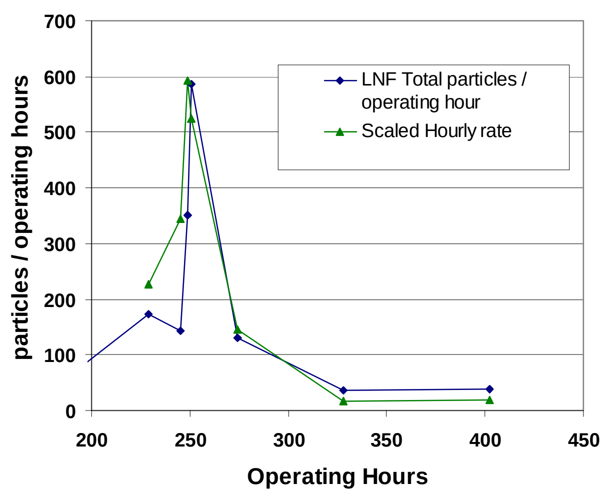

Figure 11. Comparison of LNF Measurement of Total Particles Per Operating Hour and the Scaled Magnetometer Measurement for a Helicopter Gearbox.

USS Rushmore**:** A LNF batch processor was installed onboard the *USS Rushmore* (LSD 47), a Whidbey Island class Dock Landing Ship. This instrument was connected to the ship's Integrated Condition Assessment System (ICAS) system through a fiber-optic Ethernet connection. After the LNF instrument completed a sample analysis, a series of text files containing the sample results were transferred to a local ICAS workstation. The sample analysis results were extracted and stored in the ICAS database. Several of the ship's crewmembers were trained to use the LNF instrument and used it to provide on-board sample analysis while the ship went on a six-month deployment.

Newport News Shipbuilding This site was used to baseline equipment from U.S. Navy and commercial shipboard equipment. The types of equipment examined included hydraulic, diesel and turbines. The list of equipment included the same type of machinery that was studied during the *USS Rushmore* test.

JOAP Mid-Atlantic: This site performs scheduled surveys of operational naval equipment typically using AES and various oil property tests. The LNF unit is being evaluated for its ability to augment current analysis techniques for enhancing CBM decisions. This site is also verifying the water fraction measured by LNF with more traditional measuring techniques.

Fort Campbell AOAP: Spectro Industrial Tribology Systems is participating with the Army Oil Analysis Program to expand and update its analysis capabilities for hydraulic and lubricating systems. As part of this 9-month effort, AOAP will evaluate LNF for its ability to add critical CBM information.

National Tribology: Spectro Industrial Tribology Systems is overseeing testing at the lab of National Tribology Service to compare LNF measurements against the qualitative results of analytical ferrography performed on the same oil sample.

ADM&M: This site is responisble for routine analysis of Royal Navy Air Force equipment and the assessment of new oil analysis technology. The LNF will be evaluated against SEM and analytical ferrography techniques currently employed at this site.

DSTO: This site will evaluate LNF's ability to trend abnomalities of shipboard and sub-based deisel engines and hydraulic equipment.

Advancements: During field trials, additional capabilities have been added to the LNF oil sample analysis, including oxide and fiber identification. LNF also has demonstrated the ability to detect free water suspended in lubricating fluids. Figure 12 shows the results of a controlled experiment where water was added to Mobil Jet Engine Oil II lubricant and then tested by LNF. To date, results have correlated well with expected values. The JOAP Mid-Atlantic laboratory is currently working with NRL to quantify the extent of LNF's water detection capabilities in a wide range of hydraulic and lubricating fluid types.

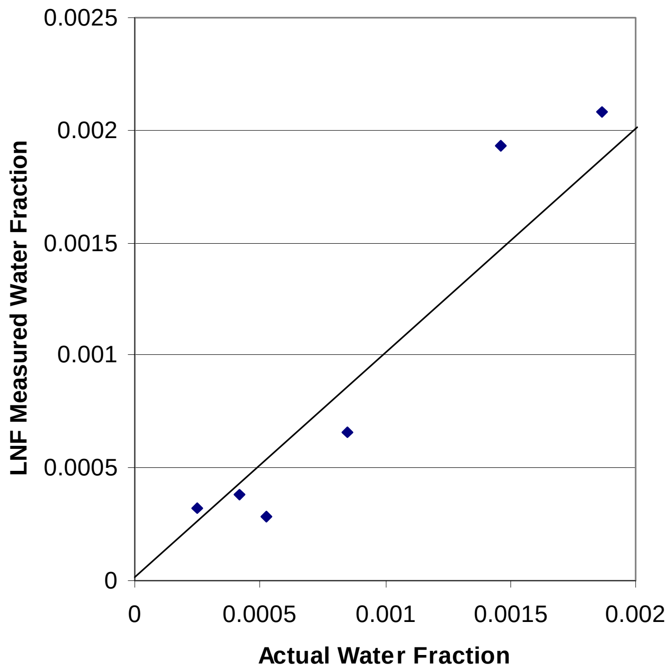

Figure 12. Experimental Results of Free Water Detection by LNF.

Summary: LaserNet Fines is an revolutionary instrument developed by the Naval Research Laboratory and Lockheed Martin to expand the capabilities of standard particle counters by adding automatic shape classification capabilities. This innovation brings to the user information on the type, severity, and rate of progression of mechanical faults and enabling informed decisions in Condition Based Maintenance.

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References:

[1] T. P. Sperring, J. Tucker, J. Reintjes, A. Schultz, C. Lu and B. J. Roylance, “Wear Particle Imaging and Analysis – a contribution towards monitoring the health of military ships and aircraft,” International Conference on Condition Monitoring, pp. 539-546, University of Wales, Swansea, UK, April 1999.

[2] B. J. Roylance and G. Pocock, “Wear Studies through Particle Size Distribution”, Wear, **90**, pp. 113-136 (1983).

[3] A. Albidewi., A. R. Luxmore, B. J. Roylance, and G. Wang, “Determination of Particle Shape by Image Analysis-the Basis for Developing an Expert System”, in "Condition Monitoring '91", M. H. Jones, J. Guttenberger and H. Brenneke, eds., Pineridge Press, Swansea, UK, 1991, p. 411

[4] B. J. Roylance and S. Raadnui, "The morphological attributes of wear particles - their role in identifying wear mechanisms," Wear **175**, 115 (1994).

[5] B. J. Roylance, I. A. Albidewi, A. R. Luxmoore, A. L. and Price, "The Development of a Computer-Assisted Systematic Particle Analysis Procedure – CASPA," Lub. Eng., **48**, pp. 940-946 (1992).

[6] B. J. Roylance, I. A. Albidewi, M. S. Laghari, A. R. Luxmoore and F. Deravi, "Computer-Aided Vision Engineering (CAVE) – Quantification of Wear Particle Morphology," Lub. Eng., **50**, pp. 111-116 (1994).

[7] T. G. Barraclough, T. P. Sperring and B. J. Roylance, "Generic-based Wear Debris Identification – the First Step Towards Morphological Classification", International Conference on Condition Monitoring, University of Wales, Swansea, UK April 1999

[8] J. E. Tucker, A. Schultz, C. Lu, T. Sebok, C. Holloway, L. L. Tankersley, T. McClelland, P. L. Howard and J. Reintjes, "LaserNet Fines Optical Wear Debris Monitor," International Conference on Condition Monitoring, pp. 445-452, University of Wales, Swansea, UK, April 1999.

[9] J. E. Tucker, J. Reintjes, T. L. McClelland, M. D. Duncan, L. L. Tankersley, A. Schultz, C. Lu, P. L. Howard, T. Sebok, C. Holloway, and S. Fockler, "LaserNet Fines Optical Oil Debris Monitor," 1998 JOAP International Condition Monitoring Conference, pp. 117-124 April, 1998, Mobile AL.

[10] J. Reintjes, R. Mahon, M. D. Duncan, L. L. Tankersley, J. E. Tucker, A. Schultz, V. C. Chen, C. Lu, T. L. McClelland, P. L. Howard, S. Raghavan and C. L. Stevens, "Real Time Optical Oil Debris Monitors," Proceedings of 51st Meeting of the Society for Machinery Failure Prevention Technology, April, 1997, pp. 443-448, Virginia Beach, VA

[11] D. D. Troyer, "Get Ready for More Soot," Practicing Oil Analysis, Vol. 2, No. 1, p. 17